International Journal of Human-Computer Studies, Volume 135, March 2020, Article number 102377
DOI: 10.1016/j.ijhcs.2019.102377

Augmented Visualization Cues on Primary Flight Display Facilitating Pilot's Monitoring Performance

Wen-Chin Li[1], Andreas Horn[2], Zhen Sun[3], Jingyi Zhang[4] and Graham Braithwaite[1]

[1] Safety and Accident Investigation Centre, Cranfield University, Bedfordshire, U.K.
[2]Flight Operation Department, Germanwings, Cologne, Deutschland
[3]Final Assembly Department, Commercial Aircraft Corporation of China, Shanghai, China
[4] Flight Technology College, Civil Aviation University of China, Tianjin, China

Corresponding author: Wen-Chin Li

Postal Address: Safety and Accident Investigation Center, Cranfield University, Martell House, Cranfield, Bedfordshire, MK43 0TR, United Kingdom

Tel: +44 (1234) 758527

E-mail:wenchin.li@cranfield.ac.uk

Content of Manuscript

Running Head: Augmented Visualization Design in the Flight Deck

Manuscript Type: Research Article

Exact Word Count of Text: 6,684 words

Abstract: 235 words

Table: 3

Figures: 3

References: 68

Biographies of Authors

Wen-Chin Li PhD C.ErgHF

Senior Lecturer, Safety and Accident Investigation Center, Cranfield University, United Kingdom

PhD in Aviation Human Factors, College of Aeronautics, Cranfield University, United Kingdom

Andreas Horn

MSc of Aerospace Vehicle Design, Cranfield University, United Kingdom

First Officer, Germanwings, Deutschland

Zhen Sun

MSc of Safety and Human Factors in Aviation, Cranfield University, United Kingdom

Avionic Engineer, Final Assembly Department, Commercial Aircraft Corporation of China, China

Jingyi Zhang

MSc Candidate of Flight Technology and Safety, Civil Aviation University of China, China

Graham Braithwaite PhD FRAeS

Professor and Head of Transport Theme, Cranfield University, United Kingdom

PhD in Aviation Safety Management, Loughborough University, United Kingdom

Augmented Visualization Cues on Primary Flight Display Facilitating Pilot's Monitoring Performance

Abstract

There have been many aviation accidents and incidents related to mode confusion on the flight deck. The aim of this research is to evaluate human-computer interactions on a newly designed augmented visualization Primary Flight Display (PFD) compared with the traditional design of PFD. Based on statistical analysis of 20 participants interaction with the system, there are significant differences on pilots' pupil dilation, fixation duration, fixation counts and mental demand between the traditional PFD design and augmented PFD. The results demonstrated that augmented visualisation PFD, which uses a green border around the "raw data" of airspeed, altitude or heading indications to highlight activated mode changes, can significantly enhance pilots' situation awareness and decrease perceived workload. Pilots can identify the status of flight modes more easily, rapidly and accurately compared to the traditional PFD, thus shortening the response time on cognitive information processing. This could also be the reason why fixation durations on augmented PFDs were significantly shorter than traditional PFDs. The augmented visualization in the flight deck improves pilots' situation awareness as indicated by increased fixation counts related to attention distribution. Simply highlighting the parameters on the PFD with a green border in association with relevant flight mode changes will greatly reduce pilots' perceived workload and increase situation awareness. Flight deck design must focus on methods to provide pilots with enhanced situation awareness, thus decreasing cognitive processing requirements by providing intuitive understanding in time limited situations.

Keywords: Augmented Visualization; Attention Distribution; Flight Deck Design; Human-Computer Interaction; Situation Awareness

1 Introduction

The automated flight deck has been accredited with benefits in operational efficiency and safety. However, automation has also increased operational complexity for pilots and created "automation-surprise" accidents (Woods & Sarter, 2000). Many of these problems have been related directly to the increasing computerization of flight deck design. The continuous occurrences of accidents and incidents as a result of insufficient situational awareness and pilots' mode confusion underline the need to develop simpler and intuitive ways of flight mode annunciations. The principle of flight deck design requires that pilots must perceive information on the flight deck in time to enable them to make decisions and take control, especially when unexpected technical errors occur (Hasse, Grasshoff, & Bruder, 2012). The different layouts of instruments and displays are designed to assist in providing a means to perceive different information as required at any particular moment (Newman & Greeley, 2001). Therefore, the capability of human information processing to perceive flight mode changes remains a safety concern in aviation. Human-centred design must offer pilots good situation awareness and decrease their cognitive workload, improving pilots' performance and reducing the occurrences of human factors errors in flight operations. There is a need to consider and integrate pilots' visual characteristics during flight deck design.

Pilots are constantly challenged with complicated situations requiring them to make timely in-flight decisions. The safety of flight operations not only require pilots precisely control the aircraft, but also have to interpret a wide range of critical information properly within a limited period of time. It is not easy to correctly predict outcomes under complex and demanding tasks due to perception and reasoning challenges related to uncertain events (Le & Wartschinski, 2018). There are lots of different visual and aural alerts in the flight deck. Donmez, Carbonell and Schneider (2009) conducted an investigation and found that continuous auditory alerts can inform human operators regarding the state of a monitored task, but the auditory alert also interfered with other ongoing tasks due to distraction of acoustic warning. The research of operators' attention distributions proposed that human attention allocation in complex and time critical situations was effectively engaged with the primary goal of target detection but was not effective in the secondary missions (Crandall, Cummings, Della Penna, & De Jong, 2011). The cognitive resources required by pilots to focus on processing different information simultaneously is problematic and may lead to human errors in the flight deck. For example, pilots' interaction with the PFD requires processing multiple sources (airspeed, altitude, attitude and flight mode changes) of information which can suffer from the restriction of human attention allocations. Therefore, providing visualization cuing to direct pilots' limited attention capacity to the needed information in dynamic situations is critical for safe flight operations. The design of augmented visualization displays in the flight deck must be tested with pilots to evaluate the effectiveness of human-computer interactions with such augmented PFD system and to identify usability issues (Dey & Sandor, 2014).

2 Human-Computer Interactions in the Flight Deck

In the aviation domain, operators, manufacturers and regulators have developed guidance documentation setting out standard requirements for flight deck design. Most of the documents focus on screen displays including various parameters such as functions, symbology, colours, and alerting design to improve Human-Computer Interaction (HCI) in the flight deck and pilot's situation awareness (SA) for safety of flight operations. Pilots must interpret parameters presented in the flight deck which may include form, contrast, brightness, symmetry and balance, colour, display format, material appearance, location, frequency and amount of information. The automated cockpit has tangled inter-human coordination and HCI in such way that one cannot understand it without addressing its myriad interconnections with the other (Dekker & Johansson, 2001).

2.1 Proximity Compatibility Principle and Pilot's SA

The principle of human-centred design can be applied to guide system development and improved simplicity and safety (FAA, 2016). The Proximity Compatibility Principle (PCP) is the most popular design principle, suggesting that related information shall be displayed in an integrated configuration, rather than in separated formats (Carswell & Wickens, 1996; Marino & Mahan, 2005). The current primary flight display (PFD) comprises autopilot modes including airspeed, altitude, attitude, heading via characters presented in the flight mode annunciator (FMA). Pilots must interpret the parameters available to them and select appropriate control modes by cross checking information in the flight deck (Burian, 2006). The FMA on the top of the PFD contains lots of dynamic information related to automatic systems and the status of flight operations. It is therefore not surprising, that a changing mode in the FMA box can be missed by a pilot whose instrument scan pattern is trained to focus exclusively on raw data parameters. This can be linked to the cognitive effort required to interpret the FMA text and projecting its future status (Mumaw, Sarter, & Wickens, 2001). Applying the principle of human-centred design in the flight deck can significantly enhance pilot's monitoring performance and reduce cognitive workload (Li, Zhang, Minh, Cao, & Wang, 2019), and increase capability to perform complex tasks (Wickens & Hollands, 2000).

Visual attention analysis can reveal the cognitive process of human-computer interaction between human operators and interface designs (Allsop & Gray, 2014; Kearney, Li, & Lin, 2016). The visual parameters offer the opportunity to investigate the relationship between pilot's SA and salient cues of alert design in flight operations (Ahlstrom & Friedman-Berg, 2006), and salient cues can attract pilot's visual attention based on bottom-up approach (Yu, Wang, Li, Braithwaite, & Greaves 2016). Visual behaviours are spontaneous responses related to the cognitive processes of human operator's situation awareness and mental state (Li, Kearney, Braithwaite, & Lin, 2018; Kuo, Hsu, & Day, 2009). Fixation is defined as the eye movement pausing over informative stimulus for the purposes of interpreting the information (Salvucci & Goldberg, 2000). The patterns of fixations on the areas of interest (AOIs) can reveal a pilot's visual attention on the tasks (Li, Yu, Braithwaite, & Greaves, 2016a). The length of fixation duration is the total time fixating on an instrument and can reflect the level of importance or difficulty in extracting information (Durso & Sethumadhavan, 2008). The nature of human beings is such that they tend to distribute longer fixation duration to relevant AOIs than to irrelevant areas (McColemana & Blair, 2013). Eye scan pattern is one of the approaches to evaluate a pilot's cognitive process and attention distributions in the flight deck using objective physiological measures (Ayaz et al., 2010). Attention blurring is characterized by a small number of fixations and increased number of transitions between instruments and without being able to actually interpret the information (Kilingaru, Tweedale, Thatcher, & Jain, 2013). Pilots' visual parameters, captured using eye tracking devices have been successfully applied to evaluate situational awareness and the effectiveness of HCI in flight deck design (Yu et al., 2016; Li, White, Braithwaite, Greaves, & Lin, 2016b).

2.2 The Complexity of Flight Mode Annunciators in the Flight Deck

Misinterpreting or missing FMA changes have been linked to many accidents/incidents in aviation. Figure 1 shows how complex the FMA can be when considering different automation modes. The labels in the red boxes depict different automation modes that are applicable in each dimension (speed, lateral, vertical, and system status). The pilot must incorporate all three components including Autothrust, Roll-mode, and Pitch-mode on the FMA to interpret AFDS status in the three-dimensional aircraft. The very nature of this design incorporates a fundamental problem, the FMA is not co-located with the flight parameters raw-data (digital numbers of airspeed or altitude) and thus does not follow the proximity compatibility principle (Wickens & Carswell, 1995). There are four red boxes in Figure 1, these include all the possible modes for each channel on B-777. The high cognitive effort required for interpretation can be demonstrated in an airspeed control scenario. The airspeed can be controlled either with the autothrust (changing thrust output in level flight) or changes in pitch (varying climb gradient or descent gradient to control speed while keeping thrust constant). If pilots want to find out whether the autothrust or the pitch-mode is controlling airspeed, they have to conduct the following tasks correctly: (1) read the FMA autothrust column text; (2) interpret the text to see if the autothrust is controlling the airspeed (as there are modes that cause the autothrust to be "engaged", but not controlling the airspeed, e.g. "HOLD" or "THR"); (3) if the text is anything else other than "SPD" (i.e. the autothrust is *not* controlling the airspeed), the scanning continues to the pitch-mode which may be controlling the airspeed in a climbing or descending scenario; (4) interpret the pitch-mode (check if it is FLCH SPD or VNAV SPD- the so-called "*airspeed on pitch*" modes); (5) check the AFDS status indication, to ensure that the autopilot is engaged in case of airspeed being controlled via the pitch-mode.

Figure 1: The complexity of information behind the FMA in the primary flight display of B-777 flight deck

Many numerous accidents and incidents related to cognitive capture and mode confusion have occured (CAST, 2008). Cognitive capture can be induced by inappropriate interface design and result in poor situational awareness. The pilot's visual information search can be fixated on irrelevant interfaces and induce attentional tunnelling vision (Dehais, Tessier, Christophe, & Reuzeau, 2010). Autothrust and autopilot (pitch mode) are traditionally separate systems onboard the aircraft, however they do interact through the physics of flight. When pilots misinterpret or miss altogether the FMA changes that tells them how the autothrust and autopilot are interacting, their situational awareness suffers from "mode confusion". Endsley (1995) defines three levels of SA, which is linked closely with the major components within cognitive processes on perception, understanding and projection. Situation awareness has been acknowledged as a critical element in a pilot's cognitive processes (Sohn & Doane, 2004). A well-known example of mode confusion leading to loss of SA is the accident involving a Boeing 777 aircraft at SFO airport. During a visual approach in clear weather conditions, flight crew actions led to several mode changes relating to the autothrust and autopilot interactions not being perceived and interpreted correctly by the flight crew, ultimately resulting in the aircraft hitting the sea wall short of the runway. A classic "pitch and power" monitoring strategy would have assisted the flight crews in an early recognition of the developing danger, but mode confusion as a result of misinterpreting or missing FMA changes meant that, as clearly shown by the investigation, the flight crew did not have sufficient situation awareness of the current status of the automation (NTSB, 2014).

2.3 Flight Deck Designs Swaying Pilot's Cognitive Processes

Automated aircraft systems not only assist in guidance and navigation tasks but become more and more involved in strategic deployment for diagnosing system health and calculating fuel-efficient routes. Therefore, these automated systems have changed pilot's task performance and decision-making. Automation is applied to moderate the human operator's task-loads and to improve situation awareness by providing a better match between cognitive resource and task requirements (Kaber, Perry, Segall, McClernon, & Prinzel, 2006). Perceived workload is an important measurement in human-machine interaction, as it is directly related to the operator's cognitive processes and the overall system performance. It represents the "cost" for a human operator to achieve a certain task requirement (Hart, 2006). The NASA Task Load Index (NASA-TLX) was introduced to capture the perceived workload of human operators by using a set of six variables including mental demand, physical demand, temporal demand, performance, effort and frustration. Furthermore, cognitively perceived workload may also impact visual parameters including pupil diameter, fixation duration and saccade (Noyes & Bruneau, 2007).

The application of eye-tracking technology to the flight deck design is constructive as it can identify a pilot's attention distribution and situation awareness on human-computer interactions (Robinski & Stein, 2013). It is critical to investigate pilot's visual attention and information processing in flight operations and their interaction with flight deck interfaces to enhance safety. Eye tracking technology can be used to evaluate pilot performance using different displays. This concept of relating visual parameters to cognitive processes has been validated by many previous researchers investigating cognitive tasks (Ahlstrom & Friedman-Berg, 2006; Salvucci

& Goldberg, 2000), scanning behaviour (Allsop & Gray, 2014), aviation training (Li et al., 2016b), and remote tower operation (Li et al., 2018). There is a necessity to understand users' perception limitations by adaptive visualizations, and this shall be integrated in the flight deck design certification process and certification requirements. The proposed augmented PFD visualization design with new, salient visual cues may reduce pilot's cognitive effort by eliminating the requirement of text-reading, and as human visual perception is affected by the saliency of an object in the field of view, it will add salient visual stimuli for critical messages on the PFD interface (Dill & Young, 2015). Pilots often must deal with time critical situations, it is important that pilots can distribute their attention effectively between the raw data and its relevant modes, as failures to manage a high-priority task in a timely manner could lead to potentially disastrous consequences (Bybee et al., 2011). Therefore, it is important to apply cognitive assistance to support pilot's attention resources on the flight deck (Chien et al., 2018).

3 Method

3.1 Participants

The experiment involved 20 participants including 4 females (20%) and 16 males (80%), aged between 24 and 47 years (M = 32.55, SD = 7.02), with flight experience from 40 to 11,000 hours (M = 1,887.25, SD = 2,565.31). As the data was collected from human participants, a research proposal was submitted to the research institute ethics committee for approval before conducting the research. As stated in the consent form filled out by the participants, the research will involve applying eye-tracker and NASA-TLX for visual behaviours and perceived workload. Participants have the right to terminate the experiment at any time and to withdraw their provided data at any moment even after the data collection.

3.2 Apparatus

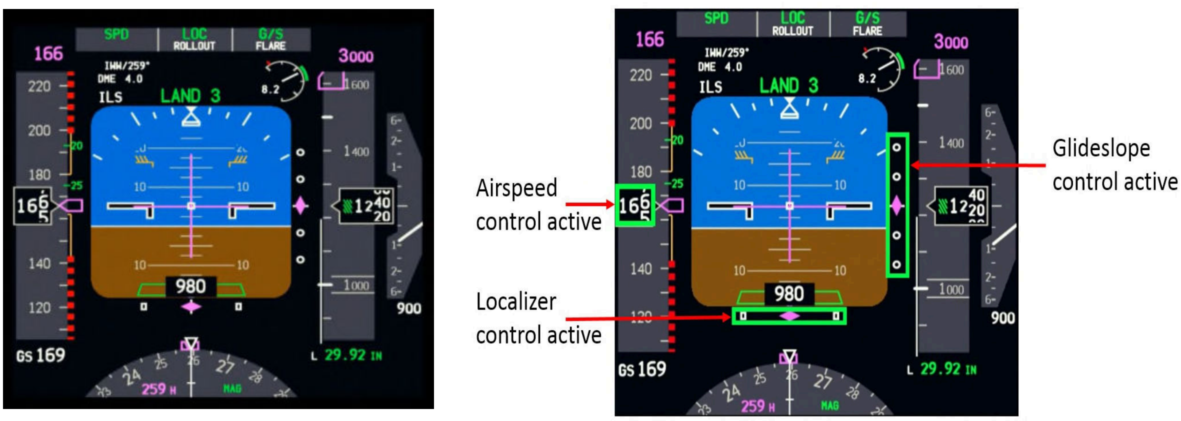
3.2.1 Eye-tracker

Pupil Labs eye tracker is a wearable, light-weight eye-tracking device. It consists of a headset including two cameras and software packages for capture and analysis. The headset is connected to any convenient computing device (e.g. laptop) using an USB. The headset hosts two cameras, one facing the right eye of the participant (eye-camera), the other capturing the field of vision (scene-camera). The eye-camera has a resolution of 800x600 pixel and a frame rate of 60 Hz. The scene-camera captures the user's field-of-view at a high-resolution

(1920x1080 pixel) with a frame rate of 60 Hz connection (Kassner, Patera, & Bulling, 2014). The pupil algorithm determines the pupil position and dimensions using the infrared picture of the eye-camera. Illumination levels were therefore kept constant during the experiment. Once the pupil data has been captured, it was transformed to the world-view using bivariate polynomials which are adjustable by the user for calibration purposes (Kassner et al., 2014). This enables the determination of the parameters, such as gaze position, fixation duration, fixation number and saccades.

3.2.2 Display of Flight Mode Annunciators

A virtual replica of the B777 instrument panel was used to create the basic scenarios. All scenarios were flown in "Microsoft Flight Simulator X". The Precision Manuals Development Group (PMDG) B777 expansion pack allowed authentic recreation of the B777 PFD and ND. The creation of a scenario was achieved using "VSDC video editor" (v4.0.1.475). While the original recording served as a basis for the conventional layout (figure 2a), the modified (augmented) display style was created by adding graphically imposed green rectangles (figure 2b), in exact synchronization with the original flight mode annunciation change time marks (frame references) in the scenario. This procedure ensured that the only difference between the two display styles was the graphically edited augmented visualization of green rectangles.



2a 2b

Figure 2a: Traditional PFD on the flight deck for ILS landing; 2b: proposed augmented visualization PFD with green boarders on activated flight modes for ILS landing

3.2.3 Scenario

The scenario is an aircraft established on the ILS landing for runway 26L at Gatwick airport, approximately 7 NM from the threshold. This represents a standard starting situation, but the subsequent mode changes are not typical and therefore unlikely to be anticipated by pilots. Using this method, the effect of display style could be investigated in both standard situations and for automation-induced mode changes. Table-1 illustrates the sequence of unexpected automation-induced mode changes during the ILS landing scenario. Pilots can only monitor and figure out passively what flight modes are currently activated based on the visual information provided by PFD.

Table 1: The flight mode sequence displayed by the FMA during ILS Landing scenario

Sequences	Auto-thrust mode	Roll mode	Pitch mode	AFDS status
01	SPD	LOC	G/S	A/P
02	SPD	LOC	G/S	FLT DIR
03	SPD	LOC	G/S	OFF
04	SPD	LOC	G/S	FLT DIR
05	SPD	HDG HOLD	V/S	FLT DIR
06	OFF	HDG HOLD	V/S	FLT DIR

3.2.4 NASA-TLX

The NASA Task Load Index (TLX) which was developed by Hart and Staveland (1988) is a common tool used to measure subjective mental workload. It relies on a multidimensional framework to derive an overall workload score based on a weighted average of ratings on six subscales including, mental demand related to the degree of mental activities would involve in the task performance; Physical demand related to the degree of physical activities involved in the task performance; Temporal demand related to the degree of time pressure on task performance; Performance related to the degree of satisfaction on task performance in flight operations; Effort is the degree of difficulty related to task performance; and Frustration is the degree of frustration and disappointment related to task performance. It is commonly used to conduct scientific research on perceived workload and it has been demonstrated in numerous studies for both reliability and validity.

All participants who completed the scenario exercise on both traditional and augmented PFD designs immediately rated their perceived workload using NASA-TLX. The goal was to assess subjective workload on the six different dimensions. Three of these dimensions reflect mental, physical, and temporal demands, whereas the remainder three dimensions feature the interaction between the operator and the task, including performance, effort, and frustration.

3.3 Hypotheses

The combination of objective (eye-tracking) and subjective approaches (NASA-TLX) serves as a basis for assessment of pilot's monitoring performance of flight modes changing. There are six hypotheses related to pilot's cognitive processes and SA and these were tested by comparing traditional PFD design with augmented PFD design as follows,

H_1: There are significant differences in pupil size

H_2: There are significant difference on fixation counts

H_3: There are significant difference on fixation duration

H_4: There are significant difference on saccade amplitude

H_5: There are significant difference on SA for mode changes

H_6: There are significant difference on perceived mental workload

3.4 Research Design

Automation-induced mode changes are typically missed by the flight crew (Björklund, Alfredson & Dekker, 2006). This research involved developing a new display concept for flight mode annunciator and verifying it using an eye-tracking device and a subjective workload measurement form the NASA-TLX. The procedures for all participants were as follows (1) provide demographic variables including age, gender, qualifications, type hours and total flight hours (5 minutes); (2) briefed on the purpose of the study and monitoring task (10 minutes); (3) calibrate the eye tracker in front of the cockpit display (3-5 minutes); (4) perform the monitoring task using the traditional (or modified) PFD, then complete the NASA-TLX (10-15 minutes); (5) perform the monitoring task using the modified (or traditional) PFD, then complete the NASA-TLX (10-15 minutes). There are two dedicated tasks created to generate realistic workload, the first task was to monitor airspeed and altitude during the entire scenario. Participants were asked to callout every 10 kt change in airspeed and every 100 ft change in altitude. This created a relative consistent workload for all participants. The second task was to monitor the flight mode annunciation field. Any change on the flight mode annunciation field had to be called out and was recorded by the instructor. The emphasis was laid on the notification of the flight mode text change, rather than the understanding of the physical meaning of the respective flight mode. The process took around 50 minutes for each participant to complete the experiment.

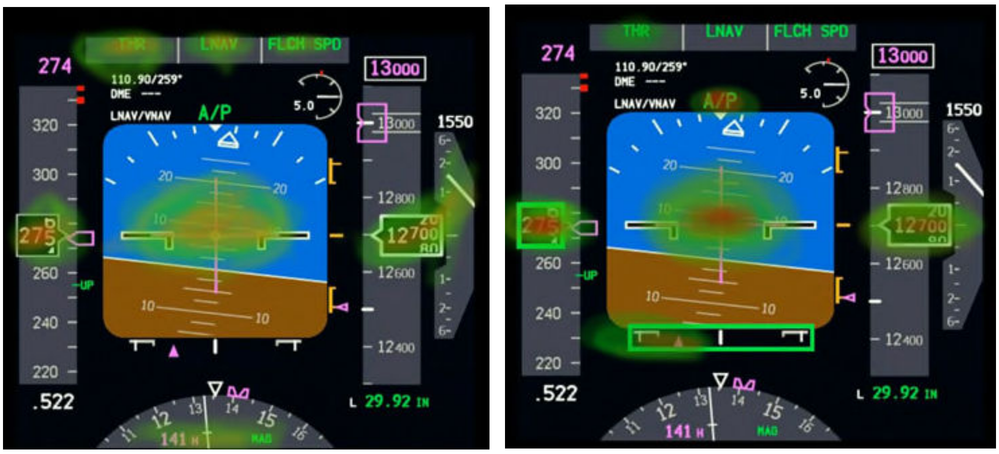
4 Results

A paired T-test was applied to compare participant's pupil dilation, fixation duration, fixation counts, saccade amplitude, and mode-changing SA (FMA callouts) between traditional PFD design and augmented visualization design by eye tracker. The results demonstrated that there were significant differences in participant's pupil dilation ($t=5.22$, $p<.001$, $d=1.074$), fixation duration ($t=2.986$, $p<0.01$, $d=.873$) and fixation counts ($t=-4.440$, $p<.001$, $d=-.667$) between two types of design (Table 2). The aggregation of fixation number and fixation duration is known as the heatmap which indicates the total amount of time spent to process the information in one display during a chosen timeline. Heatmap is associated to the positions of gaze and corresponding operator's attention distributions among the areas of interests. The heatmap demonstrated pilot's visual attention scattered widely around FMA on traditional PFD (figure 3a); on the augmented design PFD, pilot's visual attention was focussed on the raw data of parameters with the green boarder (figure 3b). The augmented visualization design of the PFD helped to direct the pilot's selective attention towards needed, useful information and free up limited cognitive resources to process other critical information. Therefore, it can facilitate pilot's understanding of the current mode in dynamic situations and assist pilots in making timely decisions. This phenomenon was demonstrated by the significantly increased numbers of mode change callouts on the augmented visualization design compared to the traditional design ($t=-5.638$, $p<.05$, $d=-1.206$).

Table 2. T-test of visual parameters and mode-changes SA between traditional design and augmented visualization design

AOIs	Design	Mean	SD	T-Test				
				t	df	p	SE	Cohen's d
Pupil Dilation	Traditional	93.227	7.042	5.220	19	.000***	1.264	1.074
	Augmented	86.624	5.095					
Fixation Duration	Traditional	.463	.111	2.986	19	.008**	0.258	.873

	Augmented	.386	.057					
Fixation Counts	Traditional	73.600	12.799	-4.440	19	.000***	1.857	-.667
	Augmented	81.850	11.939					
Saccade	Traditional	1.923	.320	2.045	19	.055	.072	.453
	Augmented	1.774	.338					
Mode-change SA	Traditional	3.500	.888	-5.638	19	0.023*	.230	-1.206
	Augmented	4.800	1.239					



3a 3b

Figure 3: Heatmap demonstrates pilot's visual attention scattered widely around FMA on traditional PFD (3a) compared with augmented design PFD (3b)

NASA-TLX has been validated to assess information-processing load associated with a wide variety of tasks (Boles, Bursk, Phillips, & Perdelwitz, 2007). In flight operations, the augmented design used the same amount of information but reduced cognitive processing duration, leading to decreased perceptual activity and time pressure. The NASA-TLX scores demonstrated that users of augmented visualization PFDs could achieve better situation awareness by perceiving the same mode changes under lower task loads. It was also found that augmented visualization PFDs relieved pilots' cognitive workload effectively compared with the traditional design. There were significant differences on participants' mental demand ($t=3.000$, $p<.01$, $d=.406$), temporal demand ($t=2.918$, $p<.01$, $d=.271$), performance ($t=-4.172$, $p<.01$, $d=-1.154$), and effort ($t=3.349$, $p<.01$, $d=.401$). However, there are no significant differences on physical demand ($t=.825$, $p=.420$, $d=.105$) and frustration ($t=1.396$, $p=.179$, $d=.170$) (Table 3).

Table 3. T-test of 6 dimensions of NASA-TLX between traditional design and augmented visualization design

Dimensions	Design	Mean	SD	T-Test				
				t	df	p	SE	Cohen's d
Mental demand	Traditional	58.250	20.018	3.000	19	.007**	2.501	.406
	Augmented	50.750	16.801					
Physical demand	Traditional	29.000	28.543	.825	19	.420	3.334	.105
	Augmented	26.250	23.501					
Temporal demand	Traditional	50.750	24.239	2.918	19	.009**	2.142	.271
	Augmented	44.500	21.818					
Performance	Traditional	61.250	16.130	-4.172	19	.001**	3.715	-1.154
	Augmented	76.750	10.036					
Effort	Traditional	56.250	21.329	3.349	19	.003**	2.612	.401
	Augmented	47.500	22.448					
Frustration	Traditional	38.000	23.697	1.396	19	.179	2.687	.170
	Augmented	34.250	20.408					

5 Discussion

The design of automation systems in the flight deck can interact with pilots in a way to assist pilots in solving problems in situations ranging well defined scenarios to ill-defined scenarios (Le, Loll, & Pinkwart, 2013). Human-centred design of automated aids have significant effects on human performance and cognitive processes (Tobaruela, Fransen, Schuster, Ochieng, & Majumdar, 2014), with increased capability to manage complex tasks (Wickens & Holland, 2000). The problematic issue with the traditional PFD design is that FMA activated modes are only highlighted for 10 seconds before any distinctive visual cues automatically disappear. Pilots also must cross check various modes in conjunction with raw parameters before they can determine which modes are in control of certain dimensions of the aircraft (figure 1). The application of an augmented visualization design PFD demonstrates that by adapting the design, situation awareness can be improved by linking the current operational context and the modes in use. The imperative hypotheses are that augmented visualization eases the user's cognitive transfer performance through distinct visual cues that guide the eye towards relevant FMA information. Visual elements guiding pilot's visual behaviours should ideally come in an appropriate visual form, with other sensory media supplementary at best (Keil, Schmitt, Engelke, Graf, & Olbrich, 2018). Flight deck design must focus on providing higher level SA directly to the pilot through the provision of instinctive understanding, which will decrease cognitive processing requirements in time limited situations.

5.1 Augmented Visualization Design Facilitating Attention Distributions

The augmented visualization PFD highlighted the activated modes related to airspeed, altitude or heading information using a green border around the relevant area. This design can help pilots to identify the flight mode status more easily, quickly and accurately compared with traditional PFD design. Response time on cognitive processes was also shortened, as shown by the significant reduction in fixation duration on augmented PFDs in comparison to traditional PFDs. Augmented visualization in the flight deck can also exert positive influence on pilots' situation awareness by generating greater attention distribution of fixation counts (table 1). In augmented PFDs, rectangles appear/disappear around the "raw" flight parameters consistent with the flight mode annunciation on top of the PFD display. This layout greatly reduces pilot's cognitive workload in determining the automation status. In fact, a quick glance at the augmented PFD is enough to understand status. Through application of augmented visualization design, the green borders on primary flight display provides cognitive assistance to pilots' information processing during the natural scanning sequences in the flight deck. The augmented design applied PCP principles to assist pilots'' acquisition of necessary information to understand critical situations and to project suitable solutions in the near future (Wickens & Andre, 1990). The shortened fixation duration for participants using the augmented PFD design serves as an objective confirmation of the faster processing time and lower subjective workload ratings mentioned by many participants. One of the key elements in pilot training is to establish an effective scanning pattern (such as basic T) and avoiding fixating too long on only one specific area (tunnelling vision) on the PFD. Differences on fixation duration was also observed by our previous research to be reflective of performance levels (Li et al., 2016b).

The results captured using the eye tracking technology also provide measures of workload. Increases in workload have been found to be associated with an increase the number of saccades and decreased saccade duration. Furthermore, measures of saccadic velocity reflect the capability of operators to respond to environment changes, to track moving targets (Hebraud, Hoffman, Pene, Rognin, & Zeghal, 2004; Rognin, Grimaud, Hoffman, Zeghal, 2004), and generally increases associated fixation durations (Van Orden, 2000; Van Orden, Jung, & Makeig, 2000). Based on statistical analysis (table 2), there are significant differences on pilots' pupil dilation, fixation duration, and fixation counts between traditional design and augmented design. Therefore, the first hypothesis (H_1: there are significant differences in pupil size), the second hypothesis (H_2: there are significant differences on fixation counts), and the third hypothesis (H_3: there are significant differences on fixation duration) can be accepted. However, the fourth hypothesis (H_4: there are significant differences on saccade amplitude) can be rejected. This research finds that while interacting with the augmented PFD design, pilots demonstrated smaller pupil dilation, shorter fixation duration and more fixation counts compared to traditional PFD. These results provide evidence that augmented visualization design can facilitate pilots' attention distribution by reducing fixation duration and increasing the frequency of fixations. The proposed "green rectangles" are one of many ways to increase the salient stimulus of a flight mode change. The key idea behind the concept is to integrate the FMA into the raw data fields. A salient design with augmented cues might be excellent at capturing the operator's attention; however, there is always a trade-off between alerting task noticeability and ongoing task performance. The prominent message may immediately divert operator's attentional resources away from the ongoing activity creating other issues such as anxiety and primary task error (Imbert et al., 2014). It is important to ensure that the added cues do not take the overriding position on the display distracting to pilot's visual scan, and thus obscuring other information which is not as salient as the activated green rectangle boarder. Furthermore, one must consider the phenomena of negative transfer and automation surprise effects due with the augmented visualization design, these are critical issues for flight deck certification and require further investigation.

5.2 A Simple Design Concept Significantly Improved Pilot's SA

The conventional style of PFD provides very little saliency for flight mode changes and only does so in the FMA box which is often excluded by pilots in their instrument scans. The current PFD contains too much complex information combining both textual and digital aura, which the pilots must decipher to control the aircraft. Due to information density, the expansion of user's perceptual ability by adaptive visualization is necessary and should be considered in the design process. The augmented visualization design is a simple concept through which the raw flight parameter that is actively controlled by the automation is highlighted with a green rectangle (see Figure 2). The results prove that the augmented PFD design was able to reduce the number of "missed" mode transitions and thus increase pilots' situational awareness. Furthermore, the augmented design follows the proximity compatibility principle (Wickens & Carswell, 1995) by integrating the FMA with relevant basic flight parameters. The design principle of intelligent cognitive assistance is mainly characterized by the goals related to enhancing human capabilities, flexibly adapt to dynamic environments, and incorporate multi-disciplinary perspectives (Le & Wartschinski, 2018). The ideal spatial positioning of information with commentary meanings can be found with augmented eye tracking technology (Keil et al., 2018). Eye tracker collected information can be used to draw a heatmap, which maps the positions of gaze and corresponding operator's attention distributions among the areas of interests (Kassner et al., 2014). A heatmap of visual parameters can be created from the positions of fixation points (figure 3a and 3b). The hot zones indicate where pilots focused their gaze with higher frequencies (Pfeiffer & Memili, 2016). The augmented design applied augmented visual cues (green boxes) on the PFD, it highlights the appropriate visual elements draw pilots' attention to the FMA changing modes thus increased pilot's situation awareness.

There is a strong relationship between pilots' situation awareness and performance (Li, Young, Wang, & Harris, 2011). Almost 40% of flight mode changes are never visually verified by the flight crew while monitoring flight status in the flight deck (Björklund et al., 2006). There were several studies which investigated pilot's situation awareness in relation to the status of the flight mode annunciator, and the findings revealed that human monitoring performance to dynamic changing modes is not reliable, especially if automation-induced mode changes occur (Mumaw et al., 2001; Miller, Barber, Carlson, Lempia, & Tribble, 2002; Björklund et al., 2006; Dill & Young, 2015). Certification requirements for transport category aircraft in Europe are laid down in EASA, and the requirements require flight deck displays to be designed to minimise flight crew errors and to display the current mode of operation (EASA, 2003). Based on table 2, the fifth hypothesis (H_5: there are significant differences on SA for mode changes) can be accepted. This research finds that pilots interacting with the augmented had better situation awareness of mode changes ($M=4.8$, $SD=1.24$) compared to traditional design ($M=3.5$, $SD=.88$). The philosophy applied in the augmented design was able to enhance pilots' situation awareness to the active mode of automation, therefore it can minimise pilot's mode confusion.

5.3 Augmented Visualization Designs Reduced Cognitive Loads

Visual parameters objectively reflect on the cognitive costs of task performance. Workload modelling as well as its management would benefit from the refinement of temporal and spatial analysis of ocular indices (Kang & Landry, 2014). Additionally, the incorporation of quantitative and qualitative assessment might enhance the identification of high workload tasks linked to accident/incident in aviation. The proposed augmented design stays within the limits of the optimum field of view, as all information is available on the primary flight display. One important aspect, when analysing situational awareness, is to look at the dynamic information in the automated systems, a concept known as "distributed situational awareness" (Stanton et al., 2007). The key concept behind the augmented design is to merge the FMA with raw flight data on the PFD and thus to embed it in the natural scanning pattern of a pilot. Additionally, the cognitive work of interpreting the FMA and correlating it with the raw parameters will be significantly reduced by simply displaying it with a "green rectangle". The analysis of pilot's visual characteristics reveals that visual parameters collected by eye tracker provide a scientific approach to investigate pilot's attention allocation and cognitive process. Whilst using the augmented PFD, pilots' pupil dilations are smaller and fixation durations are shorter (table 2) compared with traditional design. These visual parameters show that augmented PFD design reduced pilots' perceived workload (Durso & Sethumadhavan, 2008; McColemana & Blair, 2013; Li et al., 2016b).

Pilot's perceived workload has profound effects on situation awareness and quality of in-flight decision-making. Previous research shows that 75% of aviation accidents related to human error resulted from poor perceptual encoding on the flight deck (Jones & Endsley, 1996). The phenomenon might highlight how pilots' visual characteristics impact attention distribution and SA performance. High workload, competing task demands, and ambiguous cues can all contribute to the loss of situation awareness, even with experienced and well-trained pilots (Li et al., 2016b). There are different measurements for workload including primary task measure, secondary task measure, physiological measures and subjective measures. The most well-known questionnaire is the NASA-TLX which has been validated to assess information-processing load associated with a wide variety of tasks (Boles et al., 2007). Based on table 3, while interacting with augmented design PFDs, individual pilot's mental demand, temporal demand and effort are significantly lower and pilot performance is significantly higher than when interacting with the traditional PFD. Therefore, the sixth hypothesis (H_6: there are significant differences on perceived workload) can be accepted. It must be noted that there are no significant differences on physical demand and frustration, as the characteristics of flight operations mainly involve cognitive information processing and monitoring the automation systems. Pilots are not required to work physically in the flight deck, with automation aiding aircraft movements. The augmented design can facilitate pilots' information processing by heuristic cuing of green borders on the active modes of FMA, leading to a decrease of pilots' time pressure, and an increase in pilots' SA performance. The NASA-TLX scores demonstrated that the design of augmented visualization PFDs can lead to better situation awareness by helping the pilots identify the mode changes with lower mental workload.

5.4 Generalized Application of Augmented Visualization Design

The proposed augmented visualization design, based on the proximity compatibility principle, can be used as a basis to develop human-system integration in other domains, such as displays in medical care, nuclear power station, unmanned aerial vehicle, digital tower, buses and trains. The proximity compatibility principle can integrate different sources of information in close spatial proximity to facilitate operators using one gaze to catch all critical information (Wickens & Ward, 2017). It is essential to provide adequate visual information to the operator to avoid confusion and distraction. The design of autonomous vehicles must keep the operators in the loop by providing augmented visualization cues to maintain SA. There is a fundamental requirement on the design principle to keep the "operator" informed about the system's intentions and current operating modes (Debernard, Chauvin, Pokam, Langlois, 2016). The Proximity Compatibility Principle and salient design have been applied not only in aviation (Ding & Proctor, 2017; Li et al., 2019), but also unmanned vehicles (Calhoun, Ruff, Behymer, & Frost, 2018), automation technology (Yamani & McCarley, 2018), electronic medical records (Zahabi, Kaber, & Swangnetr, 2015), digital alarm systems in nuclear power plants (Liu, Hwang, Hsieh, Liang, & Chuang, 2016). The presentation of proximity information must be salient and distinctive to uphold operator's perception and support 'at a glance' information retrieval by employing pre-attentive cues such as colour, shape, opacity, or texts (Bennett & Flach 2011; Selkowitz, Lakhmani, & Chen, 2017).

The presentation of color is an important element influencing pilot's situation awareness, workload and effectiveness of human-computer interaction in the cockpit (Martins, 2016). EASA (2003) has specified using colors in the flight deck alerting design related to pilot's perceived workload. However, the application of colors in the design might have cultural implications. A culture is formed by its environment and evolves in response to changes in that environment, therefore, culture and context are really inseparable (Merritt & Maurino, 2004). Research in cross-culture ergonomics tends to concentrate on the user interface toward the use of automation (Harris & Li, 2008). Western culture tends to adopt a function-oriented model connected to a task-oriented operating concept resulting in a preference for a sequential approach to undertaking tasks inherent in checklists and SOPs. The Asian culture is for the thematic approach of task-oriented operating concept (Rau, Choong & Salvendy, 2004). There are also fundamental differences in the mental models of people in these cultures. There is a need for further investigation on the implications of colour in cross-cultural design.

6 Conclusion

Reduction of accidents and incidents is one of the most important goals in aviation and should form the basis for human-computer interactions in flight deck design. The aim of this research is to evaluate a new design concept of PFD to provide visualization cuing of mode changes on the FMA. The required cognitive efforts of human operators on monitoring tasks are similar among flight operations, medical care, train, bus, or unclear power station control rooms. It is vital to bring the “lessons learned” from the aviation history into different sectors in order to avoid a repetition of similar design flaws. Analysis of objective visual parameters of human-computer interactions on the flight deck and subjective measures of pilots’ perceived workload provided a good opportunity to compare different aspects of flight operations related to human-computer interaction. The feedback obtained from pilots revealed that the basic idea of augmented visualization design was highly appreciated for its intuitive and heuristic approach. The relatively high cognitive effort to interpret the dynamic flight mode annunciations in the flight deck, under time pressure is a contributing factor to aviation accidents. In this research, an augmented visualization PFD that was designed to improve pilot’s attention distribution, situation awareness to mode changes and reduce perceived mental workload was presented. Based on the significant improvements of pilot’s situation awareness, visual scan pattern of attention distributions and perceived mental workload, the augmented visualization PFD design proved more effective on human-computer interactions than the traditional PFD in the flight deck. Simply highlighting the parameters on PFD using green borders that are controlled by the automation greatly reduced pilot perceived workload and increased pilots’ situation awareness. It is recommended that the knowledge gained in academic research on augmented visualisation should be transferred to the certification authorities and manufacturers in order to enable a more dynamic evolution of avionics designs. The augmented visualization display is much more intuitive to catch pilots’ attention for an “unexpected”, automation induced mode changes, as the salient stimulus of visual cuing is applied directly in the raw data fields on PFD. The analysis of visual characteristics reveals that eye movements provide a scientific approach to obtain detailed information of pilot’s attention allocation and cognitive processes which are critical to human-computer interaction for future flight deck design.

Acknowledgements

This work was supported by China Scholarship Council (Grant No. 20170993005). The authors would like to express special thanks to Dr Peter Kearney and Captain Richard Homer for their substantial supports in these experiments and constructive comments on this manuscript. Our sincere thanks to all the pilots and avionic engineers who voluntary participated in this research. Their supports and enthusiasm were invaluable in facilitating the authors' research efforts.

References

Ahlstrom, U., & Friedman-Berg, F. J. (2006). Using eye movement activity as a correlate of cognitive workload. *International Journal of Industrial Ergonomics, 36*(7), 623-636. doi:10.1016/j.ergon.2006.04.002

Allsop, J., & Gray, R. (2014). Flying under pressure: Effects of anxiety on attention and gaze behavior in aviation. *Journal of Applied Research in Memory and Cognition, 3*(2), 63-71. doi:10.1016/j.jarmac.2014.04.010

Ayaz, H., Willems, B., Bunce, B., Shewokis, P. A., Izzetoglu, K., Hah, S., ... & Onaral, B. (2010). Cognitive workload assessment of air traffic controllers using optical brain imaging sensors. In T. Marek, W. Karwowski, & V. Rice (Eds.), *Advances in understanding human performance: Neuroergonomics, human factors design, and special populations* (pp. 21-31). Boca Raton, FL: CRC Press.

Bennett, K. B., & Flach, J. M. (2011). *Display and interface design: Subtle science, exact art.* Boca Raton, FL: CRC Press.

Björklund, C. M., Alfredson, J., & Dekker, S. W. (2006). Mode monitoring and call-outs: An eye-tracking study of two-crew automated flight deck operations. *The International Journal of Aviation Psychology, 16*(3), 263-275. doi:10.1207/s15327108ijap1603_2

Boles, D. B., Bursk, J. H., Phillips, J. B., & Perdelwitz, J. R. (2007). Predicting dual-task performance with the Multiple Resources Questionnaire (MRQ). *Human Factors, 49*(1), 32-45. doi:10.1518/001872007779598073

Burian, B. K. (2006). Design guidance for emergency and abnormal checklists in aviation. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 50, No. 1, pp. 106-110). Los Angeles, CA: Sage Publications. doi:10.1177/154193120605000123

Bybee, S. M., Bracken-Grissom, H. D., Hermansen, R. A., Clement, M. J., Crandall, K. A., & Felder, D. L. (2011). Directed next generation sequencing for phylogenetics: An example using Decapoda (Crustacea). *Zoologischer Anzeiger, 250*(4), 497-506. doi:10.1016/j.jcz.2011.05.010

Calhoun, G. L., Ruff, H. A., Behymer, K. J., & Frost, E. M. (2018). Human-autonomy teaming interface design considerations for multi-unmanned vehicle control. *Theoretical Issues in Ergonomics Science, 19*(3), 321-352. doi:10.1080/1463922X.2017.1315751

Carswell, C. M., & Wickens, C. D. (1996). Mixing and matching lower-level codes for object displays: Evidence for two sources of proximity compatibility. *Human Factors, 38*(1), 1-22. doi:10.1518/001872096778940750

CAST. (2008). *Mode Awareness and Energy State Management Aspects of Flight Deck Automation*. United State: Commercial Aviation Safety Team.

Chien, S. Y., Lin, Y. L., Lee, P. J., Han, S., Lewis, M., & Sycara, K. (2018). Attention allocation for human multi-robot control: Cognitive analysis based on behavior data and hidden states. *International Journal of Human-Computer Studies, 117*, 30-44. doi:10.1016/j.ijhcs.2018.03.005

Crandall, J. W., Cummings, M. L., Della Penna, M., & De Jong, P. M. (2011). Computing the effects of operator attention allocation in human control of multiple robots. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, 41*(3), 385-397. doi:10.1109/TSMCA.2010.2084082

Debernard, S., Chauvin, C., Pokam, R., & Langlois, S. (2016). Designing human-machine interface for autonomous vehicles. *IFAC-PapersOnLine, 49*(19), 609-614. doi:10.1016/j.ifacol.2016.10.629

Dehais, F., Tessier, C., Christophe, L., & Reuzeau, F. (2010). The perseveration syndrome in the pilot's activity: guidelines and cognitive countermeasures. In *Human Error, Safety and Systems Development* (pp. 68-80). Berlin: Springer. doi:10.1007/978-3-642-11750-3_6

Dekker, S., & Johansson, B. (2001). Cockpit Automation and Ab-initio Pilot Training: Report on a European Experience. *International Journal of Aviation Research and Development, 1*(2), 103-116.

Dey, A., & Sandor, C. (2014). Lessons learned: Evaluating visualizations for occluded objects in handheld augmented reality. *International Journal of Human-Computer Studies, 72*(10-11), 704-716. doi:10.1016/j.ijhcs.2014.04.001

Dill, E. T., & Young, S. D. (2015, June). *Analysis of Eye-Tracking Data with Regards to the Complexity of Flight Deck Information Automation and Management-Inattentional Blindness, System State Awareness, and EFB Usage.* Paper presented at the 15th AIAA Aviation Technology, Integration, and Operations Conference. Dallas, TX, United States.

Ding, D., & Proctor, R. W. (2017). Interactions between the design factors of airplane artificial horizon displays. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 61, No. 1, pp. 84-88). Los Angeles, CA: Sage Publications. doi:10.1177/1541931213601487

Donmez, P., Carbonell, J. G., & Schneider, J. (2009, June). Efficiently learning the accuracy of labeling sources for selective sampling. In *Proceedings of the 15th ACM SIGKDD international conference on Knowledge discovery and data mining* (pp. 259-268). New York: ACM. doi:10.1145/1557019.1557053

Durso, F. T., & Sethumadhavan, A. (2008). Situation awareness: Understanding dynamic environments. *Human Factors, 50*(3), 442-448. doi:10.1518/001872008X288448

EASA. (2003). Certification Specifications and Acceptable Means of Compliance, for Large Aeroplanes (CS-25). Cologne, Germany: European Aviation Safety Agency.

Endsley, M. R. (1995). Measurement of situation awareness in dynamic systems. *Human factors, 37*(1), 65-84. doi:10.1518/001872095779049499

FAA. (2016). *Airplane flying handbook*. Washington, DC, USA: Federal Aviation Administration.

Harris, D., & Li, W. C. (2008). Cockpit design and cross-cultural issues underlying failures in crew resource management. *Aviation, Space, and Environmental Medicine, 79*(5), 537-538. doi:10.3357/ASEM.2271.2008

Hart, S. G. (2006). NASA-task load index (NASA-TLX); 20 years later. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 50, No. 9, pp. 904-908). Los Angeles, CA: Sage. doi:10.1177/154193120605000909

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology, 52,* 139-183. doi:10.1016/S0166-4115(08)62386-9

Hasse, C., Grasshoff, D., & Bruder, C. (2012, October). *Eye-tracking parameters as a predictor of human performance in the detection of automation failures.* Paper presented at the Human Factors and Ergonomics Society Europe Chapter Annual Conference, Toulouse, France.

Hebraud, C., Hoffman, E., Pene, N., Rognin, L., & Zeghal, K. (2004). Assessing the Impact of a New Air Traffic Control Instruction on Flight Crew Activity. *Interactive Learning Environments, 19*(4), 433-446. doi:10.2514/6.2004-5104

Imbert, J. P., Hodgetts, H. M., Parise, R., Vachon, F., Dehais, F., and Tremblay, S. (2014). Attention Costs and Failures in Air Traffic Control Notifications. *Ergonomics*， *57*(12), 1817-1832. doi:10.1080/00140139.2014.952680

Jones, D., & Endsley, M. (1996). Sources of situation awareness errors in aviation. *Aviation, Space, and Environmental Medicine, 67*(6), 507-512. doi:10.1039/c4qo00187g

Kaber, D. B., Perry, C. M., Segall, N., McClernon, C. K., & Prinzel, L. J. (2006). Situation awareness implications of adaptive automation for information processing in an air traffic control-related task. *International Journal of Industrial Ergonomics, 36*(5), 447-462. doi:10.1016/j.ergon.2006.01.008

Kang, Z., & Landry, S. J. (2014). Using scanpaths as a learning method for a conflict detection task of multiple target tracking. *Human factors, 56*(6), 1150-1162. doi:10.1177/0018720814523066

Kassner, M., Patera, W., & Bulling, A. (2014, September). Pupil: an open source platform for pervasive eye tracking and mobile gaze-based interaction. In *Proceedings of the 2014 ACM international joint conference on pervasive and ubiquitous computing: Adjunct publication* (pp. 1151-1160). New York: ACM. doi:10.1145/2638728.2641695

Kearney, P., Li, W-C., & Lin, J. J. (2016). The impact of alerting design on air traffic controllers' response to conflict detection and resolution. *International Journal of Industrial Ergonomics, 56*, 51-58. doi:10.1016/j.ergon.2016.09.002

Keil, J., Schmitt, F., Engelke, T., Graf, H., & Olbrich, M. (2018, July). Augmented Reality Views: Discussing the Utility of Visual Elements by Mediation Means in Industrial AR from a Design Perspective. In *Proceedings of the International Conference on Virtual, Augmented and Mixed Reality* (pp. 298-312). Berlin: Springer, Cham. doi:10.1007/978-3-319-91584-5_24

Kilingaru, K., Tweedale, J. W., Thatcher, S., & Jain, L. C. (2013). Monitoring pilot "situation awareness". *Journal of Intelligent and Fuzzy Systems, 24*(3), 457-466. doi:10.3233/IFS-2012-0566

Kuo, F. Y., Hsu, C. W., & Day, R. F. (2009). An exploratory study of cognitive effort involved in decision under Framing—an application of the eye-tracking technology. *Decision Support Systems, 48*(1), 81-91. doi:10.1016/j.dss.2009.06.011

Le, N. T., Loll, F., & Pinkwart, N. (2013). Operationalizing the continuum between well-defined and ill-defined problems for educational technology. *IEEE Transactions on Learning Technologies, 6*(3), 258-270. doi:10.1109/TLT.2013.16

Le, N. T., & Wartschinski, L. (2018). A Cognitive Assistant for improving human reasoning skills. *International Journal of Human-Computer Studies, 117*, 45-54. doi:10.1016/j.ijhcs.2018.02.005

Li, W-C., Kearney, P., Braithwaite, G., & Lin, J. J. (2018). How much is too much on monitoring tasks? Visual scan patterns of single air traffic controller performing multiple remote tower operations. *International Journal of Industrial Ergonomics, 67*, 135-144. doi:10.1016/j.ergon.2018.05.005

Li, W-C., White, J., Braithwaite, G., Greaves, M. & Lin, J. (2016b, June). The Evaluation of Pilot's Situational Awareness during Mode Change on Flight Mode Annunciators. In *Proceedings of 18th International Conference on Human Computer Interaction* (pp. 409-418). Berlin: Springer, Cham. doi:10.1007/978-3-319-40030-3_40

Li, W-C., Young, H. T., Wang, T., & Harris, D. (2011, September). *Understanding Pilots' Cognitive Processes for Making In-flight Decisions under Stress.* Paper presented at the 42nd Annual International Seminar: Investigation a Shared Process, Salt Lake City, Utah, USA.

Li, W-C., Yu, C. S., Braithwaite, G., & Greaves, M. (2016a). Pilots' Attention Distributions Between Chasing a Moving Target and a Stationary Target. *Aerospace medicine and human performance, 87*(12), 989-995. doi:10.3357/AMHP.4617.2016

Li, W-C., Zhang, J. Y., Minh, T., Cao, J. Q. and Wang, L. (2019). Visual scan patterns reflect to human-computer interactions on processing different types of messages in the flight deck. *International Journal of Industrial Ergonomics, 72*, 54-60. doi:10.1016/j.ergon.2019.04.003

Liu, K. H., Hwang, S. L., Hsieh, M. H., Liang, S. F. M., & Chuang, C. F. (2016). Systematic layout planning in human–system interface: An evaluation of alarm displays with spatial proximity for accidents diagnosis of advanced boiling water reactor. *International Journal of Industrial Ergonomics, 51*, 30-42. doi:10.1016/j.ergon.2014.12.014

Marino, C. J., & Mahan, R. P. (2005). Configural displays can improve nutrition-related decisions: An application of the proximity compatibility principle. *Human Factors, 47*(1), 121-130. doi:10.1518/0018720053653758

Martins, A. P. (2016). A review of important cognitive concepts in aviation. *Aviation, 20*(2), 65-84. doi:10.3846/16487788.2016.1196559

McColeman, C. M., & Blair, M. R. (2013). The relationship between saccade velocity, fixation duration, and salience in category learning. *Visual Cognition, 21*(6), 701-703. doi:10.1080/13506285.2013.844965

Merritt, A., & Maurino, D. (2004), CROSS-CULTURAL FACTORS IN AVIATION SAFETY", In Kaplan, M. (Eds.), *Cultural Ergonomics* (Vol. 4, pp. 147-181). Bingley: Emerald Group Publishing Limited. doi:10.1016/S1479-3601(03)04005-0

Miller, S. P., Barber, S., Carlson, T. M., Lempia, D. L., & Tribble, A. C. (2002). A methodology for improving mode awareness in flight guidance design. In *Proceedings of the 21st Digital Avionics Systems Conference* (Vol. 2). New York: IEEE. doi:10.1109/DASC.2002.1052928

Mumaw, R. J., Sarter, N., & Wickens, C. D. (2001, May). *Analysis of pilots' monitoring and performance on an automated flight deck.* Paper presented at the 11th International Symposium on Aviation Psychology, Columbus, OH.

Newman, R. L., & Greeley, K. W. (2001). *Cockpit displays: test and evaluation*. London: Routledge.

Noyes, J. M., & Bruneau, D. P. (2007). A self-analysis of the NASA-TLX workload measure. *Ergonomics, 50*(4), 514-519. doi:10.1080/00140130701235232

NTSB. (2014). *Descent Below Visual Glidepath and Impact with Seawall Asiana Airlines Flight 214 Boeing 777-200ER, HL7742.* San Francisco, CA, USA: National Transportation Safety Board.

Pfeiffer, T., & Memili, C. (2016, March). Model-based real-time visualization of realistic three-dimensional heat maps for mobile eye tracking and eye tracking in virtual reality. In *Proceedings of the Ninth Biennial ACM Symposium on Eye Tracking Research and Applications* (pp. 95-102). New York: ACM. doi:10.1145/2857491.2857541

Rau, P. L. P., Choong, Y. Y., & Salvendy, G. (2004). A cross cultural study on knowledge representation and structure in human computer interfaces. *International Journal of Industrial Ergonomics, 34*(2), 117-129. doi:10.1016/j.ergon.2004.03.006

Robinski, M., & Stein, M. (2013). Tracking Visual Scanning Techniques in Training Simulation for Helicopter Landing. *Journal of Eye Movement Research, 6*(2), 1-17. doi:10.16910/jemr.6.2.3

Rognin, L., Grimaud, I., Hoffman, E., & Zeghal, K. (2004). *Assessing the impact of a new instruction on air traffic controller monitoring tasks.* Paper presented at *the* International Conference on Human–Computer Interaction in Aeronautics. Toulouse, France.

Salvucci, D. D., & Goldberg, J. H. (2000, November). Identifying fixations and saccades in eye-tracking protocols. In *Proceedings of the 2000 symposium on Eye tracking research and applications* (pp. 71-78). New York: ACM. doi:10.1145/355017.355028

Selkowitz, A. R., Lakhmani, S. G., & Chen, J. Y. (2017). Using agent transparency to support situation awareness of the Autonomous Squad Member. *Cognitive Systems Research, 46*, 13-25. doi:10.1016/j.cogsys.2017.02.003

Sohn, Y. W., & Doane, S. M. (2004). Memory processes of flight situation awareness: Interactive roles of working memory capacity, long-term working memory, and expertise. *Human Factors, 46*(3), 461-475. doi:10.1027/2192-0923/a000113

Stanton, N. A., Stewart, R., Harris, D., Houghton, R. J., Baber, C. McMaster, R., … Dymott, R. (2007). Distributed Situation Awareness in Dynamic System: Theoretical Development and Application of an Ergonomics Methodology. *Ergonomics*, 49 (12), 1288-1311. doi: 10.1080/00140130600612762

Tobaruela, G., Fransen, P., Schuster, W., Ochieng, W. Y., & Majumdar, A. (2014). Air traffic predictability framework–Development, performance evaluation and application. *Journal of Air Transport Management, 39*, 48-58. doi:10.1016/j.jairtraman.2014.04.001

Van Orden, K. F. (2000). Workload assessment and management for the Multimodal WatchStation. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 44, No. 36, pp. 461-464). Los Angeles, CA: SAGE Publications. doi:10.1177/154193120004403603

Van Orden, K. F., Jung, T.-P., & Makeig, S. (2000). Combined eye activity measures accurately estimate changes in sustained visual task performance. *Biological psychology, 52*(3), 221-240. doi:10.1016/S0301-0511(99)00043-5

Wickens, C. D., & Andre, A. D. (1990). Proximity compatibility and information display: Effects of color, space, and objectness on information integration. *Human Factors, 32*(1), 61-77. doi:10.1177/001872089003200105

Wickens, C., & Hollands, J. (2000). Signal Detection, Information Theory, and Absolute Judgment. *Engineering Psychology and Human Performance, 2*, 24-73.

Wickens, C. D., & Carswell, C. M. (1995). The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors, 37*(3), 473-494. doi:10.1518/001872095779049408

Wickens, C. D. & Ward, J. (2017). Cockpit Displays of Traffic and Weather Information: Effects of 3D Perspective Versus 2D Coplanar Rendering and Database Integration. *The International Journal of Aerospace Psychology, 27*(1-2), 44-56. doi:10.1080/10508414.2017.1366270

Woods, D. D., & Sarter, N. B. (2000). Learning from automation surprises and going sour accidents. In *Cognitive engineering in the aviation domain* (pp. 327-353). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Yamani, Y., & McCarley, J. S. (2018). Effects of task difficulty and display format on automation usage strategy: A workload capacity analysis. *Human Factors, 60*, 527-537. doi:10.1177/0018720818759356

Yu, C. S., Wang, E. M., Li, W. C., Braithwaite, G., & Greaves, M. (2016). Pilots' visual scan patterns and attention distribution during the pursuit of a dynamic target. *Aerospace Medicine and Human Performance, 87*(1), 40-47. doi:10.3357/AMHP.4209.2016

Zahabi, M., Kaber, D. B., & Swangnetr, M. (2015). Usability and Safety in Electronic Medical Records Interface Design: A Review of Recent Literature and Guideline Formulation. *Human Factors, 57*(5), 805–834. doi:10.1177/0018720815576827

2019-11-14

Augmented visualization cues on primary flight display facilitating pilot's monitoring performance

Li, Wen-Chin

Elsevier

Li W-C, Horn A, Sun Z, et al., (2020). Augmented visualization cues on primary flight display facilitating pilot's monitoring performance. International Journal of Human-Computer Studies, Volume 135, March 2020, Article number 102377

https://doi.org/10.1016/j.ijhcs.2019.102377